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PHOTOELECTRIC PHOTOMETERS: THEIR PROPERTIES, USE AND MAINTENANCE

By J. S. PRESTON, M.A., M.I.E.E., F.Inst.P. (*Fellow*)
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(Paper read on Tuesday, April 13, 1943)

SUMMARY

This Paper examines the problems arising in the application of emission photocells and selenium rectifier photocells to photometry. It deals with the difficulties of securing a close approximation to a linear scale, and to the spectral sensitivity of the standard eye; and also with the life, stability, and fatigue of photocells, temperature coefficient, dark-current, non-uniformity over the area of the sensitive surface, stray radiation, and the use of photoelectric instruments for measuring fluctuating light sources. In the case of rectifier cells the questions of the response of the cell to oblique illumination and of the size of cell best suited to any given purpose are also discussed. A number of colour correction filters proposed for use with both types of photocell, are cited.

The principles and methods of use of standard types of photometer circuits are described and critically discussed. The circuits included are the direct-reading and the integrating circuits for emission cells, and the light-meter, Campbell-Freeth, and balanced-cell circuits for rectifier cells. As an example of a complete instrument a new portable emission-cell photometer is described in which the amplifier circuit, comprising two stages of D.C. amplification, includes an electrometer tetrode, and gives a current gain of 2.10^7 with stability adequate for measuring photocurrents down to 2.10^{-14} ampere to within $\pm 5\%$.

The Paper is an attempt to collate the information necessary to give the user a clear understanding of the possibilities and limitations of photoelectric photometers, and of the precautions necessary to ensure results of the highest possible accuracy. Selection of this information is based on experience of the last ten years at the National Physical Laboratory. Little that is novel is described, except the circuit for use with the electrometer tetrode, and work, as yet incomplete, on the fatigue of rectifier cells under monochromatic light of different wavelengths.

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I. INTRODUCTION

The Physical Measurement of Radiation.

The three methods most often used for the physical measurement of radiation—the thermal, photographic, and photoelectric are named according to the property of radiation to which the sensitive receiver responds. In thermal instruments the radiation is absorbed as completely as possible by a blackened "target," the energy received by the target maintaining it at a steady temperature above that of its surroundings. The temperature difference is generally indicated by some form of electrical thermometer, e.g., a thermocouple or thermopile attached to, or itself forming the target. For measurements of a fundamental nature, thermal instruments are used, to the almost complete exclusion of other methods, because the blackened target is not selective in its absorbing properties over a wide spectral range; but owing to their comparative insensitivity the use of thermal methods is mainly confined to the laboratory where the necessary delicate associated apparatus is available.

In the photographic method the density of the silver deposit in the developed image is used as a measure of the intensity of the radiation to which the plate or film has been exposed. As the density of the deposit for a given radiation intensity and exposure time is by no means independent of the spectral quality of the radiation, and different plates or films coated with the same emulsion have not necessarily identical characteristics, calibration is often not a simple matter, and has to be repeated for each record. Such complications, with the need for close control of the conditions of development, make the errors as well as the inconvenience associated with photographic methods greater than can generally be tolerated for routine photometry. On the other hand, over the ultra-violet, visible, and near infra-red regions of the spectrum to which photography is suited, amounts of radiant energy far smaller than can be measured by thermal methods will give satisfactory photographic records. When long enough exposures can be given it is possible to secure photographic records at values of intensity below the reach of any other physical means except such highly specialised apparatus as the photon counter.

Photoelectric methods are of several different kinds, but all make use of the interaction between the incident radiation and the electrons present in a specially prepared sensitive surface or layer. In the PHOTOELECTROLYTIC CELL, radiation falling upon one of two electrodes immersed in an electrolyte causes a difference of potential between the two, or a flow of current through an instrument connected to them. In the PHOTOCONDUCTING CELL the radiation lowers the resistance of the sensitive material (usually selenium). Neither of these types of photocell may be used for any but the roughest of measurements because their properties are not sufficiently stable. They are, however, used for operating relays and similar apparatus. In the VACUUM PHOTO-EMISSIVE (or "glass bulb") CELL the radiation causes the emission of electrons from the sensitive surface or cathode, which under the influence of an applied electric field travel across intervening space to the anode and thence by way of the external circuit return to the cathode. The current in this circuit may be measured directly if large enough, or otherwise with the aid of valve amplification. In the GAS-FILLED CELL an inert gas at a low pressure is present, and the electrons may be accelerated until each has sufficient energy to ionise a certain number of atoms of the gas during its journey from cathode to anode. The ions are swept to the electrodes by the applied field and so augment the primary electron current. The number of ions formed per photoelectron, and so also the total current yielded, is dependent on the applied electric field. The ratio of the current for a given applied voltage to that yielded when the field is just too weak to produce any ionisation, is called the "gas-

amplification factor" for that voltage. There is a limit to the stability of the ionising process, for with a high enough field the ions first produced may acquire sufficient energy to produce others. The process then becomes cumulative and a discharge commences which can only be stopped by removing the field.

In both types of emission cell the primary electron emission is proportional to the intensity of the incident radiation, and one might therefore expect the same to be true of the current in the external circuit. In practice a close approximation to this ideal may be, but is not necessarily, achieved.

In the RECTIFIER PHOTOCELL a metal base-plate supports a layer of sensitive material, usually selenium or cuprous oxide, on which is deposited a very thin translucent metal film. Radiation penetrating this film causes an electron emission from the layer beneath, and the electrons flow, without the aid of an impressed field, into the film and from it by way of the external circuit to the base-plate, and back to their starting point. Thus, whereas the emission cell acts as a kind of valve permitting current from a battery to flow through it when radiation falls on it, the rectifier cell is a converter, and the electrical energy furnished by it is derived from the incident radiation itself. It may almost certainly be assumed that ideally the electron emission in the rectifier cell is proportional to the intensity of the incident radiation, but in practice departures from the desirable linear relation between radiation intensity and current occur to a greater or lesser degree according to circumstances. The departures are larger than for the best emission cells.

All forms of photoelectric cell are selective; that is to say, their output per unit of incident radiant energy depends upon the wavelength of the radiation. The curve relating the output per unit energy to the wavelength of the radiation is called the spectral sensitivity curve, and the function which it represents may conveniently be called the spectral sensitivity. This function depends on the type of cell and the kind of sensitive surface, and generally varies a good deal from cell to cell among those made in the same way and intended to be alike. In this the photocell resembles the photographic emulsion.

The sensitivity of photoelectric methods, including amplification when suitable, is adequate for almost all purposes. The photocell is much inferior to the human eye in sensitivity to visible radiation, but the photoelectric methods have a range comparable with the photographic, and were it not for the technical limitations which so far have made it difficult to integrate minute photo-currents over the lengthy periods of time sometimes used for photographic exposures, the lower practical limits of usefulness of the two methods would probably not differ greatly.

From this review of the three principal physical methods of measuring radiation, we see that the thermal methods are non-selective and suited to fundamental measurements; they are not sensitive enough for general comparative measurements such as are involved in photometry, though they may be used for such purposes given favourable circumstances [1, 2, 3]. Photographic methods involve a somewhat laborious technique, frequent calibrations, and large errors; their main distinction lies in their adaptability and high sensitivity. Photoelectric methods, using emission or rectifier cells, are versatile and sensitive enough for nearly all purposes, and do not require delicate laboratory equipment for their operation, while a scale closely approximating to the linear form indicated by physical theory can with care be ensured. Like the photographic emulsion, the photocell has selective properties, but since it is not "used up" by being used, these properties may be determined once for all.

Briefly, then, photoelectric methods share the advantages of both thermal and photographic methods and hardly any of the disadvantages. Nevertheless, a knowledge of general principles only is not sufficient to enable all these advantages to be combined in a given instrument, or turned fully to account where accuracy is concerned. It is necessary to attend to many technical details in order to obtain the sensitivity adequate for a given purpose, to secure close approximation to a linear scale, to overcome

difficulties due to spectral selectivity and to secure consistent and accurate results. This perhaps requires special emphasis because the degree of precision obtainable is almost always of a higher order than the highest possible accuracy, and the one is not infrequently mistaken for the other. It is with this aspect of the subject, as it relates to photoelectric photometry, that the present paper is concerned.

II. Photoelectric Photometry—General Considerations.

Photoelectric methods are supplanting the visual method of photometry largely because of their high speed of operation, and the high degree of repetitive precision generally obtainable. In many cases also they can provide a very desirable relief from eye-strain; in others the apparatus required is simpler than for visual observations. Photoelectric results are also free from the uncertainty of visual photometry arising from the variation in individual characteristics from observer to observer, which often makes it necessary to employ more than one or two observers.

The emission and the rectifier types of photocell have different general features, which fit them for different uses. The emission cell is by far the better for all purposes for which stability, precision, and linearity of scale are important, and the bulk or complexity of the apparatus are minor considerations. The emission cell is therefore largely used in laboratory work and for routine lamp photometry. The bare emission cell is not suitable for illumination measurements where the light is incident from more than one direction. For this purpose it is important that the response of the cell should vary approximately as the cosine of the angle of incidence. Generally, the presence of obstructions in the bulb of the emission cell, or even of the bulb itself, make it impossible to satisfy this condition with the bare cell. The emission cell may, however, be used behind a diffusing window having the desired property.

The rectifier cell is not such a reliable measuring instrument as the emission cell but the apparatus used with it is very simple, and so this kind of cell has great utility as a portable photometer. Also, since the sensitive surface is flat and unobstructed, the response of the cell conforms fairly closely with the cosine law, and may easily be further improved in this respect by the use of special matt lacquers or other means.

Thus, the emission cell photometer is the more generally used in permanent situations in the laboratory or works, e.g. for lamp photometry; while the rectifier cell is mainly used in portable illumination meters for which a lower accuracy is often tolerable. Nevertheless, the rectifier cell is often used for the less exacting laboratory work by reason of its convenience, while the emission cell photometer is frequently built in a portable form for varied uses outside the laboratory. One of the reasons which sometimes dictate the use of the emission cell in place of the rectifier cell is the higher sensitivity obtainable in the photometer as a whole. Emission cells suitable for photometry usually have a sensitivity of about 2 to 10 microamperes/lumen, but they can be and usually are used with certain methods of valve amplification which raise the overall value, if necessary, to about 20 amperes/lumen, without serious loss of stability. On the other hand the sensitivity of the rectifier cell alone is of the order of 500 microamperes/lumen, but its electrical properties make amplification impossible.

To ensure the highest accuracy in photoelectric photometry two requirements, the scale relation or "linearity" of the photometer as a whole and the spectral sensitivity of the cell, are fundamental. Let us consider "linearity" first. If a photometer is to be used simply to indicate the equality of two brightnesses or intensities the form of the function connecting scale reading with intensity is of no interest. The eye is almost always used in this way, to bring to equality the brightnesses of two parts of a photometric field observed simultaneously, or of the same part when it is illuminated by the two light sources in rapid alternation (flicker photometer). Photocells may of course be used in similar ways [4, 5], but the methods are often inconvenient. If, on the other hand, the

photometer is used to compare light sources of different intensities, the form of the relation between the readings and the intensities must be known. In theory, the photocell should give a linear scale relation. In practice certain features in the photocell, and in the way in which it is used, may result in departure from the linear relation. With care, one can eliminate these to a great extent, but where the photocell is concerned, only the manufacturer is in a position to do this. Not all cells at present on the market are designed with this end in view. It is thus desirable to select the cell with care and to check the departure from the linear scale. Once this has been done, however, and a satisfactory performance obtained, calibration at one or two scale readings suffices.

When a photoelectric photometer is to be used for comparing light sources of different spectral qualities the second fundamental requirement arises. It is that the photometer shall furnish results in accordance with those given by standard visual methods. Though individual eyes have different spectral characteristics, a standard luminosity function ([6]) has been agreed upon as the basis for results. The problem in photoelectric photometry is therefore to modify the spectral sensitivity of the photometer to imitate the standard luminosity function. This may be done by dispersing the light to be measured into a spectrum, which is focused upon a template shaped so as to remove different proportions of the light at different wavelengths throughout the spectrum. The light passing the template is then recombined and focused on the photocell. With a template of the proper shape the spectral sensitivity of the whole apparatus is made to match the standard luminosity function ([7]). This is, of course, a difficult laboratory method and will not be further considered here. The more common, simple method is to modify the quality of light reaching the photocell by means of a "colour-correction" or compensating filter. Though, owing to natural limitations in the properties of colour filters, it is not possible to secure an exact match with the standard eye, very close approximation can be obtained, especially when the photocell has a smooth spectral sensitivity curve which does not require much modification. The cell is of course chosen with this in mind. In certain uses, such as comparisons between tungsten lamps over a limited range of colour temperature, only partial compensation may be necessary in order to secure the desired accuracy, and the choice of an appropriate correction filter is then comparatively easy, and several different kinds may be found to serve equally well. When the radiations to be compared are of identical spectral composition as in spectrophotometry, or differ very little as in comparing a group of electric lamps of the same type and rating, no compensation at all will be needed.

The conditions of linearity and spectral sensitivity generally present by far the most troublesome problems in photoelectric photometry. There are, however, other conditions which a photoelectric photometer should obey if it is to yield accurate results without losing the advantages of simple and speedy operation. The calibration should be stable over a long period of time and the useful life of the components should be long enough to avoid inconvenient replacement and readjustment. The cell should not show undue fatigue, i.e., reversible changes in sensitivity over periods of a few minutes when exposed to light. The photometer should have as low a temperature coefficient of sensitivity as possible, and should be free from effects due to external conditions beyond the control of the operator, such as humidity, or electrical disturbances due to other apparatus or machinery. None of these questions can be adequately discussed without reference to particular types of photocell and other components, or to specific methods of use, and we shall therefore deal now with the practical considerations which should guide the user in the choice of his apparatus, and in its proper use and maintenance. Since the properties of emission cells and their methods of use are so unlike those of rectifier cells, the two classes of photometer must be treated separately. The cuprous oxide rectifier cell is not dealt with, since it is now little used,

and has been superseded by the selenium rectifier cell.

III. The Use of Emission Photocells in Photometry

1. Vacuum and Gasfilled Cells.

For photometry, vacuum cells are always preferable to gasfilled unless there is no other convenient way (e.g., by increased amplification) of attaining the desired sensitivity. The degree of gas amplification, and so the sensitivity, of the gasfilled cell depends somewhat critically upon the applied voltage, which must therefore be kept very steady in order to maintain calibration. In practice, the gasfilled cell is usually operated with a gas-amplification factor of about 8. For most cells this requires a voltage in the region of 90 volts. In the vacuum cell the current yielded for a given illumination is nearly independent of the applied voltage provided this is higher than the "saturation" voltage, i.e., the voltage above which the space-charge effect due to the electron stream in the cell is overcome, and practically all the electrons emitted at the cathode are collected by the anode. The appropriate working voltage for most vacuum cells is in the region of 20-30 volts.

2. Stability and Life.

Almost the only change which may take place naturally in the properties of a vacuum cell is one which may result if there is surplus alkali metal in the cell. The alkali metal is easily vaporised and so may be transferred on to the cathode from some other part of the cell at high room temperature, so altering the properties of the cell. The composite "thin-film" cathode of the modern cell, though it contains some alkali metal, is itself much more resistant to disruption by high temperatures.

A "clean"-looking vacuum cell, free from stray material within the bulb, is therefore to be chosen. Cells of this kind, having a central metal plate as cathode, as described in the next section below, have been in use for some time at the National Physical Laboratory. Their sensitivity has not changed by more than a few parts per cent., either absolutely, or relatively throughout the visible spectrum, over a period of some five years. There appears to be no limit to the life of emission cells when they are used intermittently, as in routine photometry, and the photocurrent drawn from them is of the order of 1/100 microampere.

3. Linearity and Fatigue.(8).

In order to secure the linear relation between current and illumination for the vacuum cell it is first of all necessary that the electric field in the cell shall be as uniform as possible, and therefore that stray charges, which might distort the field, cannot accumulate on the walls of the bulb; or, if they do, that the cathode is screened from them. In this way only can it be ensured that all the photoelectrons may reach the anode. It is a corollary that the cathode must be everywhere a good conductor. For if not the flow of photocurrent between the lead-in connection and outlying parts of the film will, on account of the resistance in the film, result in some of these outlying areas attaining such a potential that emission from them practically ceases. Owing to changing field conditions the cathode will then behave as though its effective area diminishes as the current it is called on to furnish increases, and departure from linearity will result. Moreover, on exposure to light, an appreciable time may elapse before the potential conditions over the whole sensitive area reach a state of equilibrium. During this time the current output of the cell will be diminishing, i.e., fatigue will be observed. For these reasons the "cathode-on-bulb" design of cell very seldom proves suitable for photometric use. For it is almost inevitable that in manufacture some of the sensitive material is deposited in very thin layers, having a high resistance, on parts of the bulb beyond the boundary of the silvered conducting area intended to receive it.

The design of cell which most completely satisfies all the desirable conditions is therefore one in which the cathode is a metal plate in the centre of the cell, and the anode a wire grid or mesh surrounding the cathode or screening it from the bulb walls, and producing as uniform an electric field

as possible ([9]). Cells made in accordance with this design generally exhibit only negligible fatigue, and a departure from linearity of response of perhaps only a few parts in 10,000 over a range of 10: 1 in illumination. In cases of doubt, the departure from linearity is easily checked by the summation test ([8]).

4. Types of Spectral Sensitivity, or Cathode.

Different types of cathode are sensitive to different regions of the spectrum, and by using different cells, measurements can be made in the whole range between about 2,000A. and 10,000A. Bulk metal cathodes are sensitive over comparatively narrow bands of the spectrum only (of width say 1,000A.), but composite thin-film cathodes are sensitive over much wider ranges (of extent 3000 to 6,000A.).

In photometry, when a colour filter is used in front of the cell to provide a physical "standard eye," high cell-sensitivity in the region 4000-7000A is required. Also, in order that the filter should be as simple as possible, and the overall sensitivity of the combination as high as possible, it is desirable that the spectral sensitivity curve of the cell should be of a simple, smooth type. These conditions are well satisfied by the potassium on silver oxide (or K-O-Ag) cell. This cell has a maximum sensitivity at about 3,900A. The sensitivity falls sharply at shorter wavelengths. Toward the longer wagelengths it falls regularly, approaching zero at about 8000A. As regards overall sensitivity, nothing is gained by starting with a cell like the caesium on silver oxide cell, with a high sensitivity to the unfiltered radiation from an electric lamp, when much of this sensitivity is due to the effect of radiation which the eye cannot see (e.g., infra-red) and which the proper correction filter must absorb. The more recent antimony-caesium and bismuth-caesium cathodes ([10] to [16]) should prove as suitable as the K-O-Ag cathode, with the advantage of an increase of 10 to 20 times in sensitivity, but their production in a form suitable for accurate work (as described in III., 2 and 3 above) is still awaited.

In spectrophotometry it is an advantage that the cell used should be sensitive over a wide range of wavelengths. A single cell with potassium or rubidium thin-film cathode will cover the visible region of the spectrum. The bismuth-caesium cell would no doubt also be suitable, but, as already mentioned, is not yet available in suitable form.

5. Colour-Correction Filters and Factors.

It is not possible here to go deeply into the problem of designing colour correction filters to give "standard eye" characteristics with various cells. Reference must be made to the literature for fuller details ([17], [18]). It must be emphasised at once, however, that *with no emission photocell at present available are errors likely to be small when the cell is used without a filter to compare sources of different spectral qualities.* For instance, in comparing tungsten lamps of different colour temperatures by means of a K-O-Ag cell without filter, the error is about 10 per cent. per 100°K difference in colour temperature, the photocell being more "blue sensitve" than the eye.

One of the most useful and adaptable filters for general use is a glass cell containing an aqueous solution of cupric chloride and potassium dichromate, with the addition of cobalt ammonium sulphate when close adjustment is desired. Different types of cathode may require altogether different filters, and different cells of the same kind may not be suited accurately enough by one common filter, but a filter of the following specification will, with slight modification, if necessary, suit almost any cell with the K-O-Ag cathode:—

A parallel-sided filter-cell of colourless glass containing 1 cm. thickness of a aqueous solution of

37.52g. $CuCl_2.2H_2O$
34.39g. $CoSO_4.(NH_4)_2SO_4.6H_2O$
1.353g. $K_2Cr_2O_7$

per litre of solution.

The cell should be cemented together with paraffin wax (balsam reacts with the solution), and may be hermetically sealed with a waxed

glass slip provided an air-space is left above the liquid. A filter of this kind has been in use in the lamp-testing photometer at the National Physical Laboratory for many years, without requiring any attention.

For the limited purpose of comparing tungsten lamps over a moderate range of colour temperature, full compensation is not necessary. A simpler filter is used, and adjustment of the filter by trial and error to give results agreeing with the visual scale over the limited range is a fairly easy matter. A filter like the above, but containing

20.46g. $CuCl_2.2H_2O$

1.471g. $K_2Cr_2O_7$

per litre of aqueous solution is suitable for use with a K-O-Ag cell.

An alternative method ([19]), where the photocell is housed in an auxiliary whitened sphere attached to an integrating sphere or cube, is to provide a suitable filter arranged to slide over the aperture between the two. This filter can be adjusted in position so as to modify to the desired degree the light reaching the photocell. The same principle may be applied where a diffusing window admits light to the photocell, more or less of the window being covered by the filter.

When only two types of light source, of fixed spectral composition, are concerned, as for instance in comparing sodium vapour lamps with tungsten standards of fixed colour temperature, the easiest course is to omit the correction filter altogether and determine a correction factor by preliminary comparison with accepted visual values of intensity. In applying this method to mercury vapour lamps it must be remembered that the spectral quality of the light depends on the pressure of mercury vapour, so that different types of lamp will require different correction factors. The proper correction factors should be determined for the particular cell used, as they will vary a good deal from cell to cell.

6. Temperature Coefficient.

So far we have been concerned only with properties of the photometer which are determined solely by the photocell and correction filter. In assessing the temperature coefficient of sensitivity we have to anticipate a little, and consider a part of the associated electrical circuit. The overall temperature coefficient is the sum of the individual coefficients for the cell, the filter, and the resistor R (Fig. 1) or the condenser X (Fig. 2). The temperature coefficient of most emission cells is about −0.2 per cent. per degree Centigrade, of the filter up to −0.3 per cent. and of the resistor R about −0.2 per cent. per degree Centigrade. The coefficient for the condenser X will be much smaller and can be considered negligible. The photometer as a whole will therefore have a temperature coefficient of about −0.4 to −0.7 per cent. per degree Centigrade.

7. Dark Current.

There is, however, a further effect of temperature on the photocell alone. The current which passes from anode to cathode terminals of the cell, when the cell is in darkness, is known as the dark current. In a modern well-designed cell with guard rings, in a dry atmosphere, insulation leakage contributes only an unimportant part of this current. It is in the main due to thermionic emission from the cathode. Its amount at a given temperature depends on the work-function of the cathode and is therefore related to the long-wave limit of spectral sensitivity, being greater the more "red-sensitive" the cell. In any given cell it increases with temperature. In most cells used in photometry it is too small at room temperature to cause any difficulty when direct-reading methods (IV., 1) are used. In these methods the zero-setting of the photometer (with the cell in the dark) is made with the cell in circuit and so the dark current is allowed for and not included in the reading. Variation in the dark current would, of course, result in disturbance of the zero-setting. In practice, such variations are usually so small, in the course of a single reading, that photocurrents considerably smaller than the continuous dark current on which they are superposed may be measured. When integrating methods are used, however (IV., 2), the dark current is integrated along with the photocurrent over a period of some minutes, usually. A second "dark reading"

has to be taken to determine the dark current alone, still further prolonging the element of time. The range of the variation in the thermionic emission during a single complete measurement may then be large, and so set a considerably higher limit to the smallest photocurrent which can be measured at all accurately. This point is discussed in detail below, where the two methods are described.

It is often not realised that in an infra-red sensitive caesium cell having a cathode of area 1 sq. inch, the thermionic current may be as much as 1/200 microampere at 20°C., rising to about 1/100 microampere at 30°C. The magnitude of this current and more particularly its rapid change with temperature are often serious obstacles to the use of caesium cells for accurate measurements. For special purposes the thermionic current may be reduced as desired by cooling the cell. It will obviously be less, the smaller the area of the cathode.

8. Use of Sector Disks and Measurement of Fluctuating Light Sources.

There remain to be mentioned one or two points concerning the use of emission cells in photometry, which relate to special cases rather than the general problem. The first concerns the use of photoelectric methods for measuring a cyclically varying light source. In visual photometry, sector disks are often employed to reduce the illumination on the photometer in a known ratio, and Talbot's Law is then applicable. This law, as applied to the photocell, may take the form of the statement that for a given average illumination, the mean photocurrent is the same whether the illumination be steady or fluctuating in character. This law has been found to apply accurately to emission photocells used with sector disks running at the speeds commonly used, irrespective of the degree to which the response of the cell departs from the linear form ([20, 21]). It may be assumed therefore that it holds for measurements on fluctuating sources such as electric discharge lamps, where the frequency of fluctuation is normally 100 cycles/sec. Certain precautions must be observed, however, if the characteristics of the electrical circuit of the photometer are not to introduce errors in such cases. These are mentioned below in Section IV., 1. It is also probable that the cell itself, if markedly "non-linear," would show a departure from Talbot's Law at considerably lower frequencies than are commonly encountered.

9. Stray Radiation.

The second point concerns stray radiation. Some emission photocells used occasionally for photometric or spectrophotometric purposes are quite sensitive to radiation to which the eye is relatively blind. The rubidium or caesium cell will "see" an electric lamp quite well through black material which to the eye appears absolutely opaque. Care must be taken to avoid stray radiation of this kind, not evident visibly. On the other hand the high sensitivity of the emission cell photometer makes it a useful instrument for investigating directly the amounts of stray light which may arise from inadequate screening on a photometer bench, scattering in an optical system, and so on.

10. Non-Uniformity of the Cathode.

There is one further point to note. It is that the sensitivity of the cathode of almost every emission cell is found to vary greatly over its surface. When such a cell is used to measure the intensity of a narrow beam, the light should be diffused by some suitable arrangement before it reaches the photocell, unless exceptional rigidity of the whole system, and strict invariability of the outline and relative distribution of the patch of light on the cathode, can be ensured.

These, then, are the considerations which arise in using the emission photocell for photometry. All the fundamental problems, such as linearity of scale and colour-correction, concern the cell, and not the electrical equipment with which it is used. In brief, the current which the cell delivers to the external circuit must, so far as possible, bear a certain relation to the intensity and quality of the incident light. It is purposeless to ensure this, however, unless the electrical circuit employed,

and the way in which it is used, furnish precise measurements of this current, and do not contravene the conditions necessary for proper use of the cell. We shall now, therefore, consider the electrical circuits used in emission cell photometers, and their modes of operation.

IV. Photometer Circuits for Emission Photocells

The amount of light available in most photometric work is such that with an emission cell the photocurrent is too small to be measured with a galvanometer. Generally, it is of the order of one hundredth of a microampere, and in certain applications may be very much smaller. The earliest methods of measuring such small currents employed electrostatic instruments, such as the electroscope or the quadrant electrometer. The quadrant electrometer may be used in two ways. In the first, the integrating method, the photocurrent is allowed to charge up the insulated pair of quadrants. The rate at which the potential of these quadrants changes is then proportional to the rate at which they acquire an electric charge—i.e., to the magnitude of the photocurrent. This rate is indicated by the rate at which the indication of the instrument changes, or by the inverse of the time taken for the indication to change from one given scale point to another. In the other, the direct-reading method, the photocurrent flows through a very high resistance and the electrometer is used to measure the potential fall across the resistance, this fall being proportional to the photocurrent. These are, of course, laboratory methods. They are applicable to the emission cell because its electrical characteristics are such that the small potential drop introduced into the cell circuit by the measuring system (e.g., the fall across the high resistance in the latter method) does not seriously reduce the current from the cell, except when the cell is a gas-filled one operated near its critical voltage. We shall see in the next section that in the modern method this principle can be applied in such a way that this change in voltage on the cell is avoided altogether.

In principle, almost every modern emission cell photometer is based on one or other of these two methods, but instead of the quadrant electrometer, thermionic valve amplifiers are generally used. It will fully serve the present purpose, therefore, to describe a typical circuit for each method, paying only such attention to detail as is necessary for the proper understanding and use of the photometer. We shall consider the more widely used direct-reading method first.

1. The Direct-Reading Photometer ([19, 22, 23, 24, 25, 26])

(a) Principles and Method of Use.

The direct reading photometer comprises the elements shown in Fig. 1. C is the photocell, connected in series with battery B and high resistance R, while at P connection is made to the potential terminals of a calibrated potentiometer whose resistance is negligible compared with R. A is a

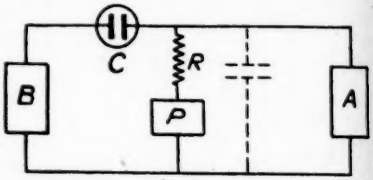


Fig. 1

D.C. valve amplifier or detector of small differences of potential, used as a null-point indicator. The procedure of operation is as follows. With C in the dark, and the dials of P at zero, the indication of A is noted. Then C is exposed to the light to be measured, and a setting of P is made so that the reading of A returns to its first value. Since the reading of A is made the same in the two cases, the net change in the voltage applied to its input is zero. That is to say, the voltage drop due to the photocurrent flowing through R has been exactly balanced out by the voltage injected (in the reverse sense, of course) at P. If P is the reading of P, and the photocurrent is i, then using the proper units $P = iR$, and, R being constant,

P is a measure of the photocurrent. We need not know the absolute value of R accurately since the photometric operations are concerned only with values relative to some standard calibration. The equation shows, however, that if it were required for instance to measure a photocurrent of 10^{-8} amp. we should use a resistor of nominal value 10^8 ohms in order to get a voltage drop of about 1 volt which can be balanced and measured conveniently with an ordinary potentiometer. If at the same time we require the precision of setting to be $\pm$ 1%, then A must be capable of indicating an out-of-balance voltage of 1% of 1 volt, i.e., 0.01 volt. Once the design of A is settled, its sensitivity is decided. This sensitivity corresponds to a fixed *increment* in the photometer reading (e.g. the 0.01 volt just taken as an example) and not a fixed *percentage* of the reading. So that the precision of setting, as a percentage, is inversely proportional to the reading. It is therefore useful to provide means for changing the value of R, and thereby the range of the photometer. In this way it can be arranged that for any series of measurements the actual voltages developed in R can be made high enough, even if the light available is small, to avoid too low a precision. In practice this means that R should be chosen so that the readings fall nicely in the middle or upper portions of the 2-volt range of P, and that the fixed sensitivity of A should be sufficiently high to give the desired precision for readings in this range of values. If, however, extremely small intensities have sometimes to be measured, the very high value of R required may necessitate permanent enclosure of this resistor (see below), in which case a sufficiently high value is chosen once for all. Higher intensities are then reduced by neutral filters or other such means to bring their readings within the (now) fixed range of the photometer.

The precision of the photometer is tested by noting the indication of A for a small known out-of-balance increment in *P*. This is a convenient way of checking from time to time the performance of A.

It might be thought simpler to dispense with P and use the *indication* of A to *measure* the voltage drop across R. However, we should then be dependent on other troublesome factors, principally the constancy of the amplification factor of A over a whole series of measurements. The null-method just described only requires the "zero-point" of A to be steady over the short time taken in adjusting P for each separate reading. In practice this zero stability is almost as important as obtaining a high sensitivity, as the two tend to be mutually exclusive, so that special valves or circuits, e.g., the Wynn-Williams bridge ([22, 23]) are commonly used to reduce the effect of drift in the voltages of the supply batteries. Another advantage of the null-method is that the cell C always operates at exactly the constant voltage imposed by battery B, whereas if P were omitted, a back E.M.F. due to the presence of R in the circuit and proportional to the photocurrent would remain uncompensated. This might be particularly troublesome if C were a gasfilled cell whose sensitivity would vary with the voltage applied to its terminals.

(b) *Working Hints and Precautions.*

The essential elements of the circuit just described are, apart from the photocell, the components P and R. P may be a standard type of potentiometer of good quality. The constancy of calibration depends also on the constancy of R. In the first place we note that most non-metallic resistors of the type commonly used have a negative temperature coefficient of resistance of about —0.2% per degree Centigrade. Freedom from dampness is important in order to maintain the constancy of R, especially if R is of high value. It is also important to keep dry all the units connected to the grid-input lead of A, in order to minimise variable leakages and consequent unsteadiness. For many purposes it is sufficient to house C, R and the input valve of A in an air-tight case (forming a convenient "photometer head") containing a drying agent. A wire gauze container with silica gel is suitable and the gel is not deliquescent. An evacuated enclosure may be more satisfactory for

very high values of R (10^{10} ohms or higher). It is then a good plan to include in the enclosure any fixed filament, anode, or other resistors comprised in A, so as to eliminate the variable cooling effects of convection currents of air. Constancy of filament current is of particular importance for stability.

Again, if R be of very high value, the valve connected to it must be of the electrometer type with very highly insulated grid. The comparatively poor grid insulation of the ordinary valve may provide a shunt path around R, which may possibly be of lower resistance than R.

Electrostatic screening is generally necessary to reduce the effects of extraneous electrical disturbances. As a minimum precaution, the photometer head unit should be enclosed in an earthed metal case. Similar enclosure of the whole apparatus is usually necessary with photometers of high sensitivity, separate units being connected together with screened cable.

A special precaution may be necessary when measuring light sources operated on A.C., especially when the intensity of the source undergoes a large cyclic variation, as with ordinary electric discharge and fluorescent lamps. The time constant of the input circuit of A must be long enough to ensure that the resulting pulses of photocurrent are effectively "smoothed" and flow away as an approximately steady current through R. If they do not, a ripple will be imposed on the input circuit of A, and if it is large enough an error in the null indication may arise from non-linear characteristics of this amplifier. In general R should be not less than 100 or 200 megohms when the lamp supply is of 50 cycles/sec. Alternatively, lower values of R may be used, and the time constant increased by adding to the inherent capacity of the grid circuit, using an auxiliary condenser of good quality connected as shown by the dotted lines (Fig. 1). The lowest value of the capacity permissible in a given instance may be estimated from the data applicable ([27]).

Well-made joints in the wiring and in the battery connections are of great importance, and so is battery maintenance. It is of advantage to give amplifier filament cells a partial discharge after each recharge or before use.

It is usual to avoid an awkward conversion factor for converting photometer readings to lumens or candlepower by suitably reducing the current in P. For example, if calibration is being effected with a lamp of 1,203 lumens, the dials of P are set at a reading of 1.203 and the current in its windings reduced with a variable resistance until a balance is obtained at that reading. Subsequent readings on test lamps measured on the same occasion are then simply multiplied by 1,000 to give lumens. The addition of a milliammeter to read the potentiometer current provides a simple means of "monitoring" the overall constancy of the apparatus. For, if the sphere paint gets dirty, or the photocell becomes less sensitive, the photocurrent for the given standard lamp falls, the voltage required to balance it likewise falls, and with it the corresponding potentiometer current as shown by the milliammeter. Routine records of the milliammeter readings over a period of weeks or months thus provide a running check on performance. Individual readings immediately reveal any gross oversight in the set-up. Of course, the method will not discriminate between deterioration of the photometer and deterioration of the standard lamp.

2. The Current-Integrating Photometer.

(a) *Principles and Method of Use.*

The integrating circuit or method can be used with valve circuits only when the grid current of the valve to which the photocell is connected is small compared with the photo-current to be measured, because the grid current is integrated along with the photocurrent. The best type of valve to use is therefore an electrometer valve—the triode for a simple single-valve circuit, or the tetrode if further valve amplification is required ([28]). The triode circuit meets practically

all photometric requirements. It is shown in Fig. 2.

The photocell C is in series with battery B and condenser X. A steady photocurrent from C will charge up X at a steady rate, the changing potential difference across X being

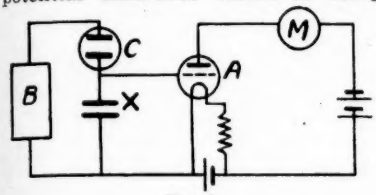


Fig. 2

applied to the grid of the electrometer valve A, and indicated by a progressively changing reading of the microammeter M in the plate circuit. Provided the battery supplies to A are stable, any given reading of M corresponds to a definite voltage across X. Thus in principle we measure a photocurrent as the inverse of the time taken for the pointer of M to travel from one chosen reading to another, i.e., for X to receive a definite fixed charge via the photocell.

In practice, a charge may accumulate on X for two reasons other than the photocurrent. One is the dark current of C plus any insulation leakages. The other is the grid current of A. In many cases these may be insignificant compared with the photocurrent, and in order to take a photometric reading we have then only to time the traverse of M from a reading M_1 microamperes to a reading M_2, and take the reciprocal of this time (i.e., the rate). If, however, the photocurrent is small, and comparable with the other factors mentioned, two timings are necessary, one with the cell in the dark, and the other with the cell illuminated. The same scale interval M_1 to M_2 is used in all cases. Thus if T_D and T are the respective times, the photometric reading is

$$\left(\frac{1}{T} - \frac{1}{T_D}\right),$$

that is, the difference between the "dark" rate and the total rate.

The precision of the instrument, apart from the question of accurate time measurements, depends upon the relative magnitudes of the "light" rate and the "dark" rate, and on the constancy of the latter. It is best estimated by actual trial. For instance, if T = 10 sec. and T_D = 100 sec., while T_D is found to vary by not more than $\pm$ 10 sec. over the period of the measurements, then the photometric reading is

$$\left(\frac{1}{T} - \frac{1}{T_D}\right)$$

= 0.1 — (0.01 $\pm$ 0.001) approx., or 0.09 $\pm$ 0.001. The uncertainty of $\pm$ 10% in the dark rate corresponds, then, to an uncertainty of only 1 part in 90 in the photometric result. It is seen that a large dark current in C will shorten T_D and thus make T_D more nearly comparable with T. In the extreme, when the dark current is large compared with the photocurrent, T and T_D approach equality and all precision is lost. In practice it is well to have T_D not less than 10T whenever possible. The choice of photocell must be therefore made with due regard to the desirability of keeping the dark current small. Cells with a large thermionic dark current will therefore be avoided if small photocurrents are to be measured.

(*b*) *Working Hints and Precautions.*

The following considerations apply in the regular use of the instrument. In the first place all connections to the grid of A must be insulated as well as possible. Therefore X should be an air condenser for preference, while the cell should be so connected that its more highly insulated electrode (usually the cathode) is joined to X and to the grid of A. The cell, valve, and condenser should be enclosed in a sealed metal box containing some dried silica gel. The sensitivity of the instrument will be higher the smaller the capacity of X, but there is no point in reducing this capacity below such a value that the dark rate becomes easily measurable in not too long a time. The condenser may conveniently be variable for altering the sensitivity to suit requirements. The sensitivity should never be so high that the time T is shortened to such a degree that the dynamic characteristics of M (e.g., damping) can come ap-

preciably into play. This point arises from the fact that, although the scale of M may be linear, the valve characteristic is not, and therefore the moving parts of M will not be rotating at constant angular velocity throughout the timing interval. Again, on account of the curvature of the valve characteristic, especially at low values of plate current, it is advisable to choose the interval M_1 to M_2 in the range of plate current above about 60 microamperes (with the usual type of electrometer triode). Care must be taken, on the other hand, that the interval chosen is below the value corresponding to a grid potential of zero with respect to negative filament; otherwise large positive grid currents flowing into X will vitiate the readings.

To reset the instrument ready for a reading, the grid lead of A may be touched momentarily by a conductor maintained at a suitable negative potential with respect to the filament. A much more convenient method in practice is to reverse battery B and illuminate C. Any photocell will give sufficient emission in the reverse sense, with sufficient light, to bring the reading of M quickly below the starting point M_1. If the desired setting is overreached, then B is again connected in the correct sense and C illuminated just sufficiently to bring the reading of M up to the desired point.

The constancy of the calibration and general steadiness over a period of time depend mainly on the steadiness of the plate and filament batteries. Ageing of the electrometer valve is a very minor consideration. The calibration is almost independent of the plate supply voltage within fairly wide limits, because variation of this voltage barely alters the shape of the (grid-volts, plate current) characteristic curve, but moves the curve bodily parallel to the grid-volts axis. A given interval M_1 to M_2 in plate current then always corresponds to the same *difference* of grid potential, or of voltage across X. The filament supply should, on the other hand, be maintained as constant as possible i.e., within, say, ± 3 per cent. of the nominal voltage. Lead-acid cells, which need not be of large capacity since the valve consumption is small, must be used.

This form of photometer is so simple and robust, and requires so few components, that it may be made quite portable. Its useful sensitivity is limited by the existence of grid-current from the valve and dark current from the cell, but is very much higher than that of any other type of portable photometer of comparable compactness. For these reasons the disadvantage of a timing procedure is not considered a serious one.

Lastly, since this photometer really measures a steady illumination in terms of exposure, it can equally well be used to measure the time-integral of a varying illumination, e.g., a flash from a photoflash bulb. This integral corresponds to the total charge communicated to X, which is measurable in terms of two static readings of M, one made before exposure to the flash, the other afterwards. Calibration for applications of this kind involves calibration of the useful scale-range of M (e.g., 40—240 microamperes) throughout in terms of exposure values—e.g., foot-candle seconds incident on the photometer.

V. The Use of Selenium Rectifier Cells in Photometry

1. General Features [29, 30, 31].

The selenium rectifier photocell consists of a sandwich of selenium between a metal base-plate and a very thin film of a noble metal. Light incident, through the thin film, upon the selenium, causes a photoelectric emission in the upper surface of the selenium, which will maintain a flow of current through an external circuit connected between the base-plate and the thin film. No outside source of electrical energy is used, the cell itself converting the radiant energy into electrical energy. The sensitivity is usually about 300-500 microamperes per lumen for light from a tungsten lamp. Included in the circuit through which the current must flow are the selenium layer and the metal film. The former has not the well-defined electrical properties of a metallic conductor, while the latter must necessarily be very thin in order to transmit as much light as possible

(probably more than 50 per cent. in practice). The resistance of the film may, in consequence, be as high as 100 ohms per square centimetre, or more. These are unusual forms of conductor, and it is not therefore surprising that the rectifier cell is not such a reliable instrument as the emission cell. It is, however, very compact and convenient to use, no batteries being necessary. A further general feature of selenium rectifier cells is that their spectral sensitivity is of one fairly well defined type. Cells made by different processes show certain systematic differences, and cells made in the same way vary amongst themselves, but all these differences are barely larger than are met with in a group of emission cells all nominally of the same type. There is as yet no wide choice of spectral sensitivity, as with emission cells. Fortunately, the curve for the selenium cell is well suited to photometric uses. It is not improbable, however, that cells with other types of spectral sensitivity may eventually appear on the market. Further reference to spectral sensitivity is made below.

2. Stability and Life.

Selenium cells preserve their properties generally unchanged over periods of some years if they are well treated. It is not yet certain whether eventual changes in characteristics result from age itself or from the amount of use that the cell gets. In this sense, stability and life are possibly not to be differentiated. It is certain that good cells will survive being exposed to an illumination of several hundred foot-candles, while in circuit, for a thousand hours or more without showing a permanent change in sensitivity of more than a few per cent.

In practice changes are liable to take place most often as a result of easily avoidable causes. Although commercial cells are lacquered on the sensitive side, dampness should be avoided. Few lacquers are completely impervious to moisture, which is certainly deleterious if it reaches the sensitive layer. Scratches which cut the lacquer, therefore, or which damage the layer, should be avoided. The contact ring or strip on the surface of the cell should not be called on to withstand unnecessary pressure, nor should attempts be made to solder leads to it. Exposure to temperatures higher than about 40° C. should be avoided, though damage may not necessarily result at this temperature. Overloading a cell by exposing it to very bright light while it is connected to a low-resistance circuit may cause damage through the burning out of the thin metal film by the large current generated. Such exposure is not known to be harmful if the cell is not in circuit, so that no current is drawn from it. As we shall see from the remarks on fatigue in the next section, measurements made to check the stability of a cell should be conducted under carefully controlled conditions.

3. Linearity and Fatigue.

The physical theory of the action of the rectifier cell is neither simple nor in all respects complete. A simple picture which describes the properties of the cell tolerably well can, however, be given. Let us suppose that the primary emission current from the sensitive layer is strictly proportional to the intensity of the illumination, but that some of this current is lost by back-leakage in the cell itself and does not appear in the external circuit. Let us also suppose that the amount of current so lost depends on the back-E.M.F. which may exist between the thin metal upper electrode and the selenium surface immediately beneath it, and which will result from the passage of current through the resistances in the circuit. If now we postulate that the back-leakage is not proportional to this back-E.M.F., but grows more rapidly, it follows that the higher the current the cell is called on to furnish the higher is the back-E.M.F. and the greater is the *fraction* of the primary current lost by internal leakage. The current available in the external circuit does not then bear a linear relation to the intensity of the incident light (unless the circuit resistance, and therefore the back-E.M.F. for any current, is zero). Finally, let us suppose that very rapid increase of back-leakage occurs when the value of the back-E.M.F. exceeds about 0.1 volt, while at some

higher value the leakage results in an almost complete internal short-circuit. This higher value would correspond to the open circuit voltage of the cell under intense illumination.

According to this picture we see that for a fixed circuit resistance, as the illumination on the cell is increased, the current generated grows and so the back E.M.F. grows, but the back-leakage grows more rapidly and so distorts the characteristic from the linear form. The higher the circuit resistance, the higher will be the values of back E.M.F. generated, over the same range of illumination, and so the greater will be the distortion of the characteristic. Similarly, for fixed circuit conditions, the higher the illumination used, the greater will be the distortion. Even if the cell is short circuited, externally, the resistances of the selenium and of the metal film have still to be traversed by the current, and so the *current in the external circuit is never strictly proportional to the illumination.* All these features suggested by our picture are substantiated in practice. It is never possible to secure a strictly linear characteristic. The nearest approach to it is obtained when the circuit resistance is zero, and the departure from it increases with circuit resistance and with illumination [32, 33, 34]. Generally speaking, when a cell of average size, say a circular cell of 45 mm. diameter, is used on short circuit, the departure may be several parts per cent. over the range 10 - 100 microamperes in current output. This error is not much increased in this current range by introducing an external resistance not greater than a few hundred ohms. On open circuit, the cell characteristic is far from linear, and the voltage developed approaches a limiting value at high illuminations. This value may be about 0.5 volt and depends on how the cell is made.

The selenium rectifier cell also exhibits fatigue which varies a good deal from cell to cell [34, 35, 36, 37]. For white light, at very low illuminations, the current output often drifts upwards slightly during exposure. At illuminations above a fraction of a foot-candle, however, the drift is almost always downward. It may not be complete until after several hours of exposure, but the larger part occurs within about ten minutes. Recovery is slow and may not be complete until the cell has been in the dark for twenty-four hours [37]. For the downward type of drift usually observed, the percentage difference between the initial and the final outputs is greater the higher the illumination, and depends also on the circuit resistance. The amount of drift under average conditions may be as much as 5 per cent. when the cell has previously been in the dark for some hours.

It is difficult to separate the effects of fatigue, and departures from linearity, so as to determine either accurately.

The voltage developed on open circuit is subject to much greater uncertainties, and the use of cells in the open circuit condition, or in voltage opposition to one another, is not recommended.

Experiments with monochromatic light on many cells at the National Physical Laboratory have shown that far larger fatigue is observed for wavelengths in the region 6,700A to 7,800A than for other parts of the spectrum. In this region, the drift is downward, and of maximum amount at about 6,800A. At this wavelength, at outputs of only 1 or 2 microamperes with short-circuit conditions, the reading may drop some 10 per cent. in a few minutes. Exposure of the cell to average daylight for a few seconds *on open circuit* will still further reduce this reading by another 10-15 per cent., subsequent recovery being fairly rapid. On the short wavelength side of 6,700A the drift at these low current outputs is comparatively very small. The fatigue effect for white light is thus presumably the integral of the varying degrees of fatigue throughout the spectrum, and is probably equivalent to a rather marked change in spectral sensitivity. The investigation of this spectral effect is as yet incomplete.

The selenium rectifier cell is thus by no means a precise measuring instrument, and its characteristics depend upon the circuit in which it is used. Fulfilment of certain conditions can minimise the possible errors, as we have seen, but careful

tests to assess their amount are often advisable.

4. Size of Cell.

Where the closest approach to a linear scale is desirable it is wise to choose the smallest cell which will give currents large enough to be properly measured at the given illuminations. For then, the current being as low as is tolerable, the back-E.M.F. on the cell due to the existing circuit resistance will be as low as possible. Moreover, the larger the cell used at a given illumination, the larger will be the current output and the larger the volt-drop in the metal film on the cell itself. With cells above a certain size, depending on the value of the illumination, this volt-drop or back-E.M.F. will, over a certain area of the cell (the central portion, for instance, of a circular cell), be large enough seriously to reduce the current output from this area. The larger sizes of cell are thus useful not so much for obtaining the largest current possible at high or even average levels of illumination, as for obtaining sufficient current to measure when the illumination is very small.

When the area which can be illuminated is limited it is best in any case not to use a cell larger than this area, so that the whole surface of the cell may be illuminated and the uncertain shunting effect of unilluminated cell-surface avoided.

5. Surface Variations in Sensitivity.

When the quantity to be measured is not the illumination, but the quantity of light (or "flux") in a well-defined beam, the whole beam must, of course, fall within the sensitive area of the cell. It is then important to keep the location of the illuminated area of the cell fixed, for the sensitivity is seldom quite uniform over the surface of the cell ([38], [39]). For a given size of beam it is preferable for the cell to be only just large enough to receive the whole beam. If the beam is intense enough to permit of it, the best arrangement is to allow the beam to fall on a translucent diffuser such as opal glass, and measure the illumination at a fixed distance of a few centimetres behind it. The light can then be fairly evenly spread over the whole surface of the cell. The diffuser and the cell should be mounted together as a single rigid unit.

6. Spectral Sensitivity.

Nearly all selenium rectifier cells now on the market have the same type of spectral sensitivity curve, not unlike the luminosity curve for the average eye, though the curve for the cell extends further at both ends of the spectrum ([40]). The sensitivity is highest at about 5,500A. and falls on either side to 50 per cent. of the maximum at about 4,000A, and 6,400A. In the red the cut-off is not very definite and there is some sensitivity well into the infra-red. This may result in errors in certain kinds of measurement if it is overlooked. Individual cells show appreciable differences in spectral sensitivity within the same general type.

The Weston Photronic Cell Type I. has a spectral sensitivity curve somewhat different from the above ([41]). Its shape is much the same, but the maximum lies at 5,900A. The Photronic Type II. cell is of the more usual class described above.

The Emby cell is of a type intermediate between the two types of Weston cell.

It is probable that all cells of the common class are made from purified selenium. The influence of other ingredients on the spectral sensitivity has been noted in the literature ([42], [43], [44]). Tellurium may be added to increase the red sensitivity and therefore also the total sensitivity to light from tungsten sources, but this is of no advantage in photometry, because the cell is thereby made markedly different from the average eye in spectral qualities. It appears that the character of the thin upper electrode has no major influence on the spectral sensitivity, no doubt because it is so thin, and therefore not highly selective in any case.

7. Correction Filters and Factors.

The errors likely to arise from the use of the selenium rectifier cell without a filter for the photometry of tungsten lamps over a limited range

of colour temperature are not large. If a curve is plotted of the ratio

$$\frac{\text{photoelectric "luminosity"}}{\text{visual luminosity}}$$ against

colour temperature of the source it is found that the ratio has a minimum value at a colour temperature which, for most cells, is within the range 2,500°K to 3,000°K. If the cell is standardised against a tungsten lamp at this particular colour temperature, the error in using it to measure a lamp at any other colour temperature is thus always positive. The curve is a fairly flat one and the error will be less than a few per cent. within 200°K or so on either side of the minimum point, and only becomes rapidly greater for colour temperatures well outside this range. It is thus seen that a cell standardised against a normal tungsten source will "read high" either with daylight or with a carbon filament lamp. The appropriate correction factors for different types of source vary a good deal from cell to cell, especially for highly selective sources. Some approximate values, based mainly on the literature ([45, 46, 47]) are tabulated below. These are adjusted to refer to calibration against tungsten at 2,848°K.

Type of Source	*Multiple readings by* *Photronic I.*	*Other Cells*
Tungsten 3,000° K..	1.01	0.97
Carbon filament ...	0.92	0.90
Incandescent gas mantle	1.14	1.03
Daylight (overcast)	0.90	0.70
Mercury 400 - W. H.P.	1.40	1.07
Mercury-fluorescent ("white")	—	0.90
Sodium vapour.....	1.35	1.20

A number of different filters have been proposed for use as correction or compensating filters for securing "standard eye" results directly. None of these can be assumed to suit *every* cell of a given type, and their comparative merits have not been the subject of extended trial, except in the case of the Viscor filter specially designed to suit the Photronic Type I. cell. Of these filters the following deserve mention, but for further details the references must be consulted. The first filter has the merit of being adjustable.

I. ([48]) ..... 5 mm. thickness of an aqueous solution containing 10 per cent. $CuSO_4$ and 0.2 to 0.4 per cent. $K_2Cr_2O_7$.

II. ([49]) ..... Schott glasses GG10 (2mm) + BG9 (3mm).

III. ([50]) .... Schott glasses VG2 (1mm) and OG1 (1mm), each covering only part of the cell.

IV. ([51, 52]) Gelatine film containing Naphthol Green 0.287 g/sq. metre. Naphthol Orange 0.038 g/sq. metre. Tartrazin 0.268 g/sq. metre.

V. ([53, 54])... Schott glasses GG10 (2mm) + BG15 (10mm); or OG4 (2mm) + BG18 (1mm). These are quoted as being suited to the Photronic cell.

VI. ([41]) .... The Viscor filter made commercially for the Photronic I. cell.

8. Temperature Coefficient.

When a correction filter is used, its temperature coefficient of transmission must be taken into account in the coefficient for the whole photometer. The coefficient for the filter will depend on the kind of filter used, but an average figure is –0.2 per cent. per degree Centigrade. For the cell itself it is impossible to give an exact figure, because the coefficient is dependent on the resistance of the external circuit and on the illumination level ([55, 56]). In nearly all cases it will be within the range of ±1.5 per cent. per degree Centigrade, and most probably the figure will be about –0.3 for average practical purposes. The coefficient for the instrument used to measure the cell output must also be included. That of a good microammeter will be negligible. If the Campbell-Freeth circuit (see below) is used, however, the temperature coefficient of the resistor in this circuit must not be forgotten. It will be negligible if the resistor be wire-wound, but if a graphitic type of re-

sistor be used the coefficient will be about –0.2 per cent. per degree Centigrade. Thus for the whole photometer the temperature coefficient will generally be between –0.3 and –0.7 per cent. per degree Centigrade, the precise value in a given case depending on the apparatus used.

We now turn to the use of rectifier cells in certain specific applications. The first is the measurement of illumination.

9. Response to Obliquely Incident Light.

The output of the ordinary rectifier cell falls off more rapidly than the cosine of the angle of incidence, as the cell is rotated to positions more and more oblique to the incident light (assumed to come from one direction only). The defect in the readings obtained with specially made cells, having nearly optically flat sensitive surfaces, and coated with a glossy lacquer, has been shown to be almost exactly attributable to the increasing fraction of the light reflected by the lacquer surface ([29]). The behaviour of commercial cells with a glossy lacquer is very similar. It results in low readings under oblique illumination, and incorrect evaluation of the illumination from an extended source, such as the sky. For uniform hemispherical illumination the error, if the cell is calibrated with normally incident light, is about 8 to 10 per cent. For directional illumination at an angle of incidence of 70°, with the same calibration, the error is about 18 per cent., and increases rapidly for larger angles of incidence. The use of a matt lacquer gives some improvement, especially for directional illumination at large angles of incidence. This expedient is hardly worth while, however, because where such large angles are involved, as in measuring the illumination on a road surface due to distant lamps, it is better to place the cell normal to the light (dealing with each light-source separately if there are several of them) and multiply the reading so obtained by the cosine of the angle between the vertical and the direction of the source.

When a cell is to be used with oblique illumination it is, of course, very important that the cell mounting shall not project more than absolutely necessary in front of the plane of the cell surface.

Numerous devices have been described for obtaining better "cosine response," involving modifications or additions to the cell. Few of these are very convenient for general work ([57 to 62]).

A complication arises when it is desired to use a rectifier cell for general illumination measurements with light sources of various spectral qualities. A filter is not then satisfactory for colour correction. In the first place, the reflection losses at the filter surfaces will vary with the angle of incidence, and so increase markedly errors of the kind just considered; and, in the second place, the thickness of filter traversed by the light will depend on the angle of incidence. An artifice is then adopted by which the instrument is made suitable for use with a limited number of types of light source. On the indicating instrument the same scale serves for all these types of source, but a different instrument shunt is used for each, the shunt appropriate to a given case being selected by a selector switch. These shunts, in fact, apply the appropriate colour correction factors for the respective light-sources electrically, and their values have to be calculated or adjusted in accordance with these factors when the instrument is made.

10. Use of Sector Disks and Measurement of Fluctuating Light Sources.

Another special case, in the use of rectifier cells, is their employment for measuring fluctuating light sources, such as electric discharge lamps, or light interrupted by a sector disk. There is very little information available on the behaviour, in these circumstances, of the cells or of the circuits used with them. It is certain that when the indicating instrument is a microammeter, and the inertia and damping of the movement hold the indication steady, the reading will correspond strictly to the average value of the fluctuating direct current from the cell. This

average current, on the other hand, is certainly not determined by the mean illumination only. It depends on the resistance in circuit, of course, as for steady illumination, but for any given resistance it also depends on the frequency of interruption or fluctuation of the light. As the frequency is increased, the cell current approximates more and more closely to the value it would take if the illumination were of the same mean value, but steady in character. The frequency necessary to ensure a given degree of approximation is higher the higher the circuit resistance.

This effect of frequency can easily be seen by using a cell of 45 mm. diameter in conjunction with a sector disk of 10 per cent. transmission (two sector openings), setting the cell circuit resistance at 1,000 ohms and adjusting the illumination to give a reading of, say, 10 to 20 microamperes, and then varying the speed of the disk over a moderate practical range.

In the absence of more complete knowledge of this effect, it is possible simply to recommend the use of the lowest possible circuit resistance for measurements on discharge lamps (whose frequency is fixed), or with sector disks, and with the latter to keep the disk speed as high as possible.

Whether or not the output of a cell, in microampere-seconds, produced by a single flash of light is proportional to the flash intensity is also a matter which awaits further investigation. Ballistic methods of using rectifier cells have been the subject of only one careful investigation (63), and therefore little useful information is available for recapitulation here.

VI. Photometer Circuits for Rectifier Cells

It has been shown that the selenium rectifier photocell can only be used with reasonable accuracy as a photometer if the circuit resistance is kept low. In addition, the illumination, and therefore also the photocurrent, should not exceed what is necessary for the purpose in view. This involves a limitation of the voltage available across the circuit. In a typical case, in which the circuit resistance is, say, 200 ohms, and the photocurrent 100 microamperes, the voltage on the circuit is 20 millivolts. The order of accuracy with which it is possible to measure the current, using a galvanometer, is very considerably higher than that with which it is possible to measure a voltage of 20 mV. using a D.C. valve amplifier or thermionic voltmeter. The limitations of the photocell thus rule out the use of valve amplification as an aid to sensitivity or precision.

1. The Simple Light-Meter.

The simplest circuit comprises merely the cell and a galvanometer of suitable range and resistance. The limitations imposed on the meter resistance by considerations of linearity of scale have already been discussed. These limitations may be relaxed to some extent if no assumption is made as regards proportionality, and the light-meter as a whole is calibrated on a photometer bench. On the other hand the deliberate use of high circuit resistances to distort the output curve of the cell so as to obtain a logarithmic scale (as in some photographic exposure meters) militates greatly against prolonged stability of calibration. It is clear that any change which may take place in the cell, resulting in a change in the internal cell-leakage-path in shunt with the meter, will have a more serious effect the higher the meter resistance. The use of shunts in illumination meters to provide for use with different types of light source, has already been noticed.

A point sometimes forgotten when using a cell with an uncalibrated galvanometer is that the angular deflexion of any but the very best moving coil galvanometer is seldom strictly proportional to the current over any appreciable scale range. Errors then noticed may not always be due to the behaviour of the cell.

2. The Campbell-Freeth Circuit.

With a suitable circuit it is possible to eliminate altogether the effect of resistance in the circuit external to the photocell. This is done by arranging that the potential difference at the cell terminals is zero while the

current output is being measured. The circuit, which admits of various modifications in practice, is usually known as the Campbell-Freeth circuit (64, 65). The principle of the circuit is shown in Fig. 3.

C is the photocell, G a sensitive galvanometer, R a resistor of fixed

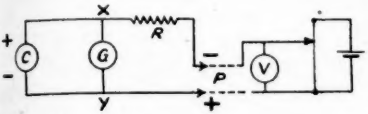


Fig. 3

value, and P a source of potential connected in such a manner as to "help" the current round the circuit, *not* to oppose the voltage generated by the photocell. It is then possible, when the cell is exposed to a given illumination, to apply a potential difference at P such that the galvanometer G shows no deflexion. When this is so, the potential difference between points X and Y in the circuit must be zero, and the conditions are equivalent to a short circuit, so far as the photocell is concerned. At the same time, since no current flows through G, the whole of the photocurrent i must be flowing through R and P, and in this loop of the circuit the condition $P + iR = O$ must be satisfied, since the potential difference between X and Y is zero. Thus P is a measure of the photocurrent.

The instrument used at P may be an ordinary potentiometer used as a potential divider, provided only that the photocurrent which must flow through it is too small to cause appreciable errors in its scale indications. In practice this means that the internal resistance of P must be small compared with R. The value of R is of course chosen to suit the range of P and the expected value of photocurrent. If the current i is 10 microamperes, and is to be measured by the application of a potential difference of 1 volt at P, then the above equation shows that R should be 100,000 ohms. Instead of a potentiometer at P, we may use an uncalibrated slide wire, or slider-resistance, with a voltmeter permanently connected across the tapped portion, as shown to the right of the dotted connections in Fig. 3.

In addition to securing short-circuit conditions on the photocell, this circuit has also the advantage that the galvanometer G may be chosen solely on the grounds of its sensitivity. It is used as a null instrument, so that scale proportionality does not matter, and as it is not in circuit with the photocurrent a high resistance is no disadvantage.

This is a very useful circuit since it dispenses with the sensitive galvanometer as the current meter, and uses it simply as a null instrument, the measurements being made on an instrument in which a linear and much more extended scale is readily available. No matter how small or how large the photocurrent, the scale range is readily changed to suit the conditions by altering the value of R. The ultimate sensitivity is, however, determined by that of the galvanometer.

The fact that the photocell operates under short-circuit conditions does not eliminate entirely such defects as departure from a linear characteristic, for as has already been pointed out, the effect of resistances such as that of the selenium layer and the upper metal film in the cell itself must still remain.

The only precautions necessary in using this system are to ensure that any changes in ambient temperature are not such as to change the value of R appreciably, if a graphite resistor is used, and that the insulation of the system is good, especially when the photocurrents being measured are small, and G is of high sensitivity in consequence.

3. The Divided, or Balanced Cell Circuit (66).

A divided cell or double cell system is often used to indicate a balance between two illuminations. For instance, two beams of light derived from the same light source pass, one through an absorbing medium whose density is to be measured, the other through a neutral or other type of wedge. Measurement of the unknown density is achieved by adjusting the wedge until a balance is obtained between the outputs of two cells receiving the light in the respective

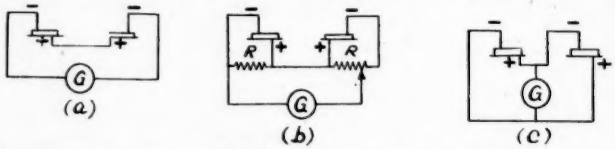
beams. The advantage of this principle of operation is that fluctuations in the intensity of the light source are compensated.

Sometimes a cell is used in which the sensitive surface has been divided by a fine cut across the centre line or diameter of the cell. A sensitive galvanometer is connected between the two halves of the upper surface, the circuit being completed by the common base-plate of the cell. Such a system may be used to indicate, by null-deflexion, when a spot of light is centrally disposed across the dividing line of the cell, or to detect a small movement from this position.

Circuits of this type are shown in Fig. 4.

In circuit (a) Fig. 4 two cells or two halves of the same divided cell are

Fig. 4



(a) (b) (c)

connected in opposition through the galvanometer G. Zero deflexion of G then indicates equality in the *voltages* developed by the two cells. The open-circuit voltage of the rectifier cell is, however, one of its most unstable features, so that the indications of this system are by no means so reliable as those of circuit (b). In this, the circuit of each cell or half the same cell is completed separately by means of a suitably low resistance R. A galvanometer connected between the two upper cell electrodes then indicates a balance of *current* outputs from the two cells. If under the desired conditions the two cells give unequal currents, the galvanometer can still be made to give zero reading by connecting it to an appropriate tapping on the resistance carrying the greater current, as shown on the right hand resistance in the diagram.

A simple circuit, which is as sensitive as (a) and also provides for operation of the cells under the ideal short-circuit condition, is shown in (c) Fig. 4. It cannot be used with a divided cell, however. Two separate cells are connected in series, with the galvanometer across the two connecting links. When the galvanometer reads zero, the voltage across the terminals of either cell must be zero (short-circuit condition), and also the currents generated by the two cells must be equal. There is one very minor drawback to this circuit, viz., that no electrical adjustment is possible (as it is in the case of circuit (b)) in order to secure a null reading when the currents from the two cells are not equal. The currents must of necessity be equal for a null reading, and appropriate adjustment of the light falling on the cells is thus required.

VII. Miscellaneous Applications and Methods

It has been possible in this survey to describe the basic types only of circuits used in photoelectric photometers. Many elaborations of these have been devised. The object of some of these is to provide results in some form other than that of readings on a simple linear scale. In the photographic exposure meter a geometric relation between meter deflexion and illumination is often preferred, the illumination being doubled for equal successive scale-steps. In the daylight recorder means are provided for obtaining a continuous trace of the readings. A neon flasher circuit may be used to integrate readings over a period of time. This produces a series of electrical impulses whose frequency is proportional to the light intensity, and whose total number in a given time may be recorded by a counter.

In another class of instrument the photocell is used as a comparator in order that its defects as a measuring instrument may not come into play. A good example is the rectifier cell photometer of MacGregor Morris and Stainsby ([32]), in which a number of such defects are simultaneously disposed of. Finally, there is a large class of instruments in which un-

usual circuits are used, exploiting to the full some special technique or component in order to satisfy some particular requirement (e.g., portability or high sensitivity) which cannot easily be met by simple means. This class of instrument is constantly being added to as new or improved components become available, such as the secondary emission or multiplier photocell. Even a relatively simple factor, such as the availability of a non-deliquescent and easily regenerated drying agent like silica gel, can have considerable influence on instrument design.

It is clear that such a field could not be covered in a single paper, but the following references are given to form a starting point for any more detailed exploration of the instrumental side of the subject:

(67) Emission cell spectrophotometer.

(68, 69, 70) The Hardy Recording Spectrophotometer.

(71, 72, 73) Colour - matching with emission cells.

(74) High-sensitivity directly indicating photometer with emission cell. An interesting modern valve-circuit.

(75, 76, 77) The rectifier cell as a photometer. Properties, precision, and accuracy.

(78) Contains very extensive references to application to densitometry, spectrophotometry, colorimetry, etc.

(79) A full and critical review, to 1934, of methods of densitometry.

(80) Photometry. Survey of recent progress and useful references.

(81) A very full review of physical photometry for the period 1935-1939, and almost complete references for that period.

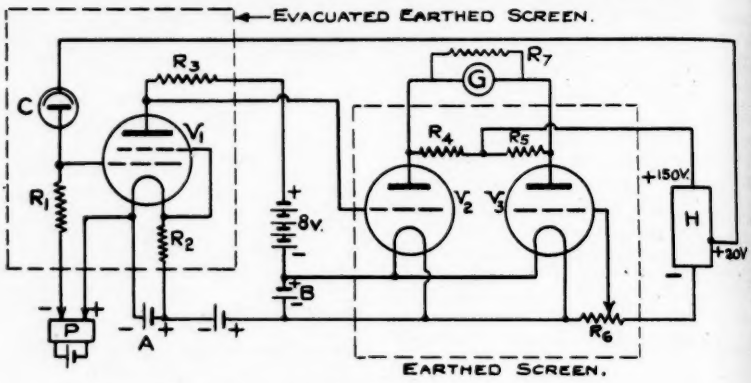
In conclusion, it may be of interest to describe a photometer recently built for miscellaneous applications at the National Physical Laboratory. It illustrates many points considered in this paper. It may also serve as a simple introduction to the purely technical aspect, and to this end the essential details of design and operation are given as briefly as possible.

VIII. A Typical Emission Cell Photometer

The requirements of this photometer were as high a sensitivity as possible without loss of accuracy or undue limitations on portability and adaptability. These considerations led to the choice of the principle exemplified in the circuit of Fig. 1 and of a vacuum cell having good characteristics, though not a high sensitivity. The overall sensitivity was then made as high as possible by using a photocell coupling resistance of very high value, and a two-stage D.C. amplifier. High amplification was desired because it was necessary that a fairly insensitive portable galvanometer should be used as the indicating instrument in the output connections to the amplifier.

The circuit is shown and the components listed in Fig. 5. In the input stage the high value of the resistor in the grid circuit made necessary the use of an electrometer valve, the tetrode being chosen to provide for resistance coupling to the second stage. In this stage the bridge-arrangement of two valves was used in order to give better stability and freedom from effects of drift in supply voltages. The use of the electrometer valve in the first stage also simplifies the method of coupling between the stages. Since the anode potential of the electrometer is relatively low, a direct anode-to-grid connection between the stages may be used without placing the whole of the second stage at some inconveniently high potential with respect to earth, as would be the case if the input valve were of the commoner class requiring a high tension supply of perhaps 150 volts.

With the supply voltages shown, adjustment and operation of the circuit is as follows. The appropriate standing grid bias for the tetrode is determined in the usual way by trial. The value of bias for which a small change in bias produces the maximum change in anode current is found. The standing bias is then set to this value to the nearest 0.1 volt. In the circuit shown this bias was found to be −1.0 volt,



V_1	Osram electrometer tetrode
V_2, V_3	Mullard P M 1 A triodes
C	Osram photocell K M V 6
R_1	Dubilier 10,000 megohm resistor
R_2	10 ohm wire resistor
R_3	Dubilier 250,000 ohm resistor
R_4, R_5	Dubilier 50,000 ohm resistors
R_6	500 ohm grid potentiometer, wirewound
R_7	2,000 ohm shunt
G	Tinsley portable galvanometer, 25mm. microamp., 300 ohms resistance
P	Cambridge decade vernier potentiometer, reading to 0.1mV
H	150 volt dry battery
A, B	2 volt 20 ampere-hour lead-acid cells
	The remaining batteries in the supply to the electrometer anode consist of 2 volt lead-acid cells of 5 ampere-hour capacity.

Fig. 5

approximately, with an anode current of 40 microamperes. The bias may conveniently be left permanently set on the first decade dials of P, the remaining dials reading from 0.09 volt downwards being used for photometric readings.

The appropriate grid voltage for operating the following triode valve (as determined from its characteristic curves) is set by connecting the triode filaments to the appropriate 2-volt cell in the anode supply to the tetrode, and then making a final adjustment by adjusting the value of the ¼ megohm (nominal) interstage coupling resistance. The output bridge is then finally balanced by adjusting the setting of the automatic bias on the other triode. It is to be noted that the filament, grid, and anode resistors in the circuit of the tetrode are included within the evacuated screening tube containing the photocell and tetrode, so as to ensure stable values of resistance.

In making a photometric measurement, the output galvanometer is set to a suitable indication (not necessarily zero) by adjusting the automatic bias setting in the output bridge, the photocell being in darkness. The cell is then exposed to the light, and the galvanometer indication brought back to its original setting by setting the appropriate reading on P.

This circuit has been found to be quite satisfactory in operation and free from tendency to drift if the batteries are partly discharged before use. The sensitivity of the amplifier is such that a voltage change of 1 millivolt at the input, equivalent to a photocurrent of 10^{-13} ampere, produces a current of about 2 microamperes in the output galvanometer. The photocurrent is thus amplified in the ratio of some 20 million to one.

and the overall sensitivity, with a photocell giving 2 microamperes/lumen, is 40 amperes/lumen. Short-period fluctuations are observed on the galvanometer, which, with the damping provided, have a scale range of about 1/20 microampere. This figure therefore represents the amount of uncertainty, due to instability, in a single reading. It corresponds to the equivalent of about 2.10^{-15} ampere in photocurrent, or 10^{-9} lumen incident on the photocell. The instrument will thus measure, with a precision of $\pm$ 5%, 10^{-8} lumens, correspondng to an illumination on the photocell of about 2.10^{-6} ft.c. This limit would be increased to about 5.10^{-6} ft.c. by the use of a correction filter on the cell.

IX. Conclusion.

In this survey of the application of photoelectric cells to photometry we have noticed their advantages over the thermal methods, and over the photographic plate. These include speed of operation, high precision (in most cases), and ready adaptability to very versatile requirements. The difficulties which arise are of two kinds, namely, those connected with the particular scale to which the results must conform, and those connected more exclusively with the technical aspect. On the one hand, there are the problems of colour correction, "linearity" of scale, and measurement of diffuse illumination. On the other, there are the effects of temperature, moisture, mechanical ill-treatment, and so on. Together, these questions cover a fairly wide field with both scientific and technical aspects. These aspects are so closely bound up with each other in photoelectric photometry that consideration of one without the other is almost valueless where the practical aim of obtaining accurate results is concerned.

It has been thought worth while, therefore, to collate as much of the relevant information as it seems possible to include in a single paper. The principal omission concerns the design of valve circuits for use with emission photocells. However, the circuit given finally in this paper forms a link, and a sufficient guide to the expert in valve technique to show him what are the essential features, as far as he is concerned, of the photoelectric photometer. Beyond this point the interest of the average illuminating engineer ceases, and the remainder of the problem of design can be left to the specialist in that field.

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DISCUSSION

The CHAIRMAN (Dr. H. Buckley) said that what had appealed to him was the essentially practical character of the paper, and as he was probably the only one present who had seen a copy of the full paper he could say that it was encyclopaedic in its scope and would form a splendid contribution to the Transactions of the Society. It was nearly ten years since the Society had had a paper on photoelectric photometry, and Mr. Preston had shown what improvements had taken place in that period.

Mr. G. T. WINCH said that the author had given such a complete survey of the subject that there was little to add.

He had been very interested in the

suggestion for the need to put the emission type of photocell in an evacuated or drying chamber, where high grid resistance values were used in order to obtain high light sensitivity. Ten years ago he had come to the same conclusion, and as the result had developed the Photocell Photometer Unit in which the electrometer triode, grid leaks, and photocell were all mounted in one evacuated glass envelope; these units had been commercially available since 1936.

The extent of the linearity of response was very important in measuring applications, and measurements on linearity measuring apparatus which he had described in 1938 indicated that the KMV6 type photocell was linear in its response to within 5 parts in 10,000 over a 10 to 1 ratio in incident light.

In order to obtain the highest limiting sensitivity to light, it was essential that a photocell should have a very small or preferably no dark current. If the dark current was large, then an appreciable residual voltage was developed across the grid leak which often resulted in loss of photocell excitation potential and this was difficult to compensate. The fortuitous fluctuations in dark current tended to cause instability and "noise," thus limiting the ultimate sensitivity which might otherwise be achieved and it often happened that a cell of less sensitivity in terms of micro-amps per lumen, had a higher limiting sensitivity when used in conjunction with a suitable amplifier, because of its small dark current.

With regard to the rectifier cell, did he understand the author to say that in general this type of cell showed departures as large as −18 per cent. from the value at normal incidence when the cell was illuminated at 70 degrees from the normal? If that were so, then the author appeared to have been unfortunate in his selection of cells, because many cells were treated with a matt cellulose finish which, up to that angle, showed departures of only about −5 or −6 per cent. Sometimes the error was positive by 1 or 2 per cent, and generally he did not think that the situation was as bad as the author suggested.

As to the Campbell-Freeth circuit, that was certainly a useful circuit, especially as it enabled the rectifier type cell to be operated under short circuit conditions, using a sensitive high resistance galvanometer for indicating the balance condition. In his own work he had found that it was not always the short circuit condition that gave the nearest approach to linearity of response. Moreover, the departures from linearity of response often varied largely with the individual photocells.

Referring to the testing of photocells, both emission and rectifier type, he pointed out that nowadays random samples were taken from the bulk manufacture and tested for initial characteristics, after which they were life tested for 300 hours or more. This was a routine procedure for ensuring the maintenance of photocell quality.

Mr. G. S. H. Mogford said that it did not necessarily follow that the use of rectifier cells in lightometers gave correct readings, although many people assumed this to be the case.

There were two main sources of error, the first being due to colour and the other to the angle of incidence of the light reaching the cell. In the case of colour, multiplication factors were issued by the manufacturers for various sources of light, but usually these were of a very general nature and with any specific measurement a certain error was to be expected.

The correction factors were also affected by the wall and ceiling reflection, and it can be readily appreciated that in the case of a small room illuminated by a single mercury lamp the light reaching the plane of measurement was dependent not only upon the lamp but also upon the colour of the walls, ceilings, etc.

The use of a suitable filter to correct the response curve of the cell to a close approximation of the visibility curve, enables a direct reading of the lightometer to be obtained from the colour point of view, but unfortunately in most cases it increases the error due to light reaching the cell at high angles of incidence.

With regard to the effect of angle of incidence, the error caused by this is often exaggerated by the glass cover fitted to protect the surface. The speaker found that the error with this type of cell was much higher than the 10 per cent. quoted, it being possible to obtain an error as high as 25 per cent., although in standard general lighting installations the overall error was in the region of 13 per cent.

As the lightometers are now utilised by many users it is desirable to make some attempt to educate them on the proper use of the instruments. Many illumination measurements are taken and accepted at lower values than is really the case, solely due to the inability of the cell and its glass covering to obey the cosine law. In the case of lighting systems put forward by commercial firms, this can, in certain cases,

cause bad feeling either with the lighting consultant or with the instrument manufacturers, when the errors are pointed out to the user, at what must seem a very convenient time, by the consultant.

Dr. J. W. T. WALSH thanked the author for stressing the difference between precision and accuracy. It was important to remember that because an instrument repeated itself to a very high degree of precision it did not necessarily follow that accuracy was being obtained. Those of the older generation in photometry, who had been used to depend upon their eyes, were a little suspicious and uncomfortable when everything was put in a box and an instrument was read at the other end. There was sometimes a lurking fear that they might be unconsciously misled by the apparatus. However, it had to be recognised that with the photoelectric method it was possible to measure brightnesses or illuminations of an order which were quite impossible of measurement previously with any accuracy at all. The photoelectric photometer was to be welcomed, for its higher sensitivity and for the greater ease and comfort it gave the observer, and it had been developed to a very high degree of perfection as the author had demonstrated.

With regard to the angle of incidence of the light, mentioned by Mr. Winch, in many cases, and particularly in street lighting, this was a serious difficult. In street lighting there were instances in which the light was so close to the horizontal that it was impossible to use the instrument in the horizontal position; it had to be used with the cell normal to the light and a correction was made afterwards. He was rather surprised that Mr. Winch questioned the percentage correction mentioned by the author, because his own experience was that this was often higher than —18 per cent. The author had not mentioned, when presenting the paper, the various devices which had been brought out for correcting automatically for the drop in sensitivity of the cell as the obliquity of the light increased.

In connection with the use of large rectifier cells, the author had mentioned the difficulty of using anything but a very low illumination. Had any experiments been made on the lines of providing a central contact in addition to the circumferential contact, or possibly several contacts at different parts of the cell surface, to get over that difficulty? There would not appear to be any mechanical objection, and it might prove useful in certain circumstances.

Lieut.-Col. K. EDGCUMBE asked the author for a further explanation of his reference to 1,000 hours as the life test of these cells at 200 ft.c. If the foot-candles had been lowered he would have been inclined to increase the number of hours. Did the author regard any particular foot-candle illumination as the maximum to which the cell should be subjected? On the question of fatigue, he said he had not realised before that it was the infra-red rays that caused fatigue. Would it be advisable, when testing for fatigue, to insert a filter and keep out the heat rays? Mention had been made of the advantages of using a small cell because the current had not so far to go. If one wanted more current than could be obtained from one cell, would it not be preferable to have two cells in parallel rather than one large cell?

He supported Mr. Winch with regard to the effects of angularity and thought the author had been rather pessimistic about it. His own experience was that a matt varnish was quite useful and enabled a very much lower figure to be obtained than the figure given by the author. He preferred not to have a glass cover as the damp was bound to get in in our climate, and it was very difficult to dry it out again with the glass cover in front.

Mr. G. F. FREEMAN, speaking on the question of colour correction factors—and calling attention to those due to Mr. Dow in the February and March issue of "Light and Lighting"—said the trouble very largely was what happened to the light after it left the source. This also included transmission from glassware fittings. Therefore he felt it would be better to provide some colour correcting filter and get away from correction factors. His own main experience had been in connection with the photometry of fittings, and that should be handled on a different basis from the photometry of light sources. He had found rectifier cells satisfactory as long as they were placed far enough away from the fitting. There should be a distance of not less than 10 ft. in the case of a 24-inch fitting. With regard to stray light, one of the advantages of the photoelectric cell was that it released the observer from having to concentrate on the photometer head. Personally, he appreciated being able to look round to see where the stray light came from. It was difficult to screen

from stray light if one was a long way from the source, and the best way was to obstruct the direct light and measure the stray light separately and deduct it from the total.

Professor J. T. MacGregor-Morris asked about the relative accuracies of the various methods adopted for extending the range of selenium cell photometers, such as the incorporation of a switch, the use of a single diaphragm, or of a diaphragm having several notes, and especially as to the order of the errors involved. He also stressed the point that in his view when a portable photometer was supplied it should be stated that the readings were probably correct to say within 5 or 10 per cent. and at the same time some idea as to their relative importance should be given. Mr. Preston would probably remember that Mr. Stainsby and himself worked for some time on rectifier photometers. They had been so much troubled with corrections that they decided to eliminate them completely. They had accordingly put two cells back to back and rotated them so that each faced alternately one source of light and then the other. This eliminated temperature correction, the difference of fatigue of the two cells, and colour differences. This method had been used by them for about two years running the instrument several hours a week and there had been practically no trouble.

With Mr. Preston he would much like to see a satisfactory explanation of the operation of the Campbell-Freeth circuit.

Mr. R. Maxted said that, speaking with ten years' experience of rectifier cells in laboratory and field measurements, he was very satisfied with the performance obtainable. The author had very skilfully and correctly magnified certain cell characteristics. He thought it important that the data given in the paper should be regarded as of great value in the development of accurate rectifier cell technique, and should not be accepted merely as evidence of the existence of pitfalls. It was essential to seek an accurate conception of the physics of any instrument, such as the rectifier cell, so that applicational techniques could be devised to give full utilisation of the inherent advantages while limiting the effect of undesirable characteristics.

The influence of angle of incidence afforded a simple illustration of the avoidance of an inherent limitation. He presumed that when the author mentioned large errors, he was referring to hemispherical illumination, involving all angles to 90 degrees. This condition rarely occurs in practice, and most measurements involve angles within 45 degrees where the error is negligible. Even in measuring general room illumination, the majority of the light was received at angles less than 60 degrees, and the error may be 2 to 3 per cent. Only a small percentage of the total light is received at greater angles, and the error is therefore of the second order. He had recently made a careful investigation in connection with measurements on 5 ft. tubular lamps to satisfy himself on this point.

Reference had been made to the subtle distinction between precision and accuracy. [It appears that precision denotes consistent or repeatable performance, whereas accuracy refers to the correctness of method and result.] Amongst those who accepted only visual methods, there seemed to be an almost superstitious belief that the precision of the rectifier cell was *ipso facto* proof of inaccuracy. This belief seemed to arise from experience of the limitations of visual methods where a close agreement between readings sometimes aroused suspicion. The attitude was not always consistent, because precision was expected and accepted from other electrical devices, such as voltmeters, upon which the accuracy of visual photometry depended.

In this connection, he remarked that if the linearity and precision of microammeters were equal to that of some rectifier cells, cell photometry would be still more reliable. In his early experience most difficulties arose from secondary electrical and mechanical matters. Inconsistent results were due mainly to a failure to appreciate the electrical significance of the mechanical mounting of the cell plate. Inaccuracy arose from neglect of fatigue to red and infra-red energy, and this was overcome on polar co-ordinate photometers by the use of filters.

The basic characteristics of cells were not found to be limiting factors because, as the author had shown, precise laws could be discovered and utilised in devising accurate methods. In comparative photometry greater accuracy was obtainable with cells than with visual methods. In absolute measurements the cell can, of course, be no more accurate than the calibrations available from the visual evaluation of energy.

Referring to the linearity demonstration, he was surprised at the 7 per cent. error shown. In recent similar tests his colleagues had not been able to detect the error, and he would be glad if the author would indicate cell illuminations

involved in the demonstration. In another recent investigation it was found that with 1 milliamp. passing through the cell, the linearity was surprisingly good, and was better than had been obtained with earlier cells at 20 micro-amps. He thought the divergence between the author's experience and his own would be explained by differences between individual cells. It was possible to select cells with excellent characteristics, although he doubted whether sufficient was yet known of the physics of the cell to ensure a uniform production.

Mr. C. I. WINSTONE said he had been a practical photometrist with the selenium cell since 1934, when he bought his first instrument of this type. It had been used in street lighting tests twice a week up to the war with great success. At first the factor used was 1.17, but it had frequently been calibrated, although, after all these years, the factor had only altered to 1.33. The important thing in the use of this instrument was to see that it was definitely a one-man instrument, and in his own case the instrument had been used all the time by himself only. The result was that to-day it was as good as ever it was. When one remembered what had to be done at night years ago in regard to street lighting with the visual photometer, the advantages and convenience of the photo-electric cell type were enormous. The selenium cell would give a true reading early in the evening or at 12 o'clock at night, when one's eyes were tired, which was a great advantage. Again, with this type of photometer it was possible to see fluctuations of light immediately, which was not possible with the visual photometer in the case of very small fluctuations. Mr. Preston had said that red fatigued the photometer, but he himself happened to be working on gas, in which the red did not predominate in the light emission from the mantle, and therefore he took it that better results from this point of view would be obtained than with another form of light in which red predominated. Finally, he asked Mr. Preston what his experience had been with a temperature of more than 75 deg. F. Would it definitely damage the cell?

Captain MURRAY asked the author why the rectifier type of cell was not so suitable for cine purposes as the other types.

The CHAIRMAN said that before calling on the author to reply there were two questions he would like to put. One had already been mentioned by an earlier speaker. Would not it be possible to use a contact strip, on a rectifier cell, in the form of a spiral, so that the path of the current in the sputtered metal film would everywhere be very short? That would have the effect of cutting down the sensitive area of the cell, but it would have compensating advantages in other ways.

The other question was with regard to the fact that it was peculiar that the rectifier cell should show fatigue to wave-lengths in the red but not to shorter wave-lengths not very far away from the red. What caused this differential selective effect in fatigue? During the past ten years there had been a number of improvements in rectifier cells, and it would be interesting to know what had been done specifically to produce these improvements.

Mr. J. S. PRESTON, in reply, first thanked the speakers in the discussion for filling in many gaps in the paper. He agreed with Mr. Winch that in order to obtain the highest sensitivity in a photometer using an emission cell it was most important to choose a cell with a small dark-current. The sensitivity of the cell was of less importance. It was, therefore, best to avoid cells with a high red-sensitivity. He was aware, of course, that matt lacquer was often used to improve the polar curve of response of rectifier cells. Close conformity with the cosine law at very oblique angles might certainly be important in certain cases, as in street lighting measurements. On the other hand, this might be obtained at the expense of a greater departure from the law at less oblique angles, i.e., in zones which might often be the most important, as in general daylight or indoor measurements. He thought this sometimes was the case when a matt lacquer was used, though he had made no recent measurements on commercial cells so treated. He was inclined, therefore, to agree with Mr. Maxted that a matt lacquer was perhaps an unnecessary refinement. For many purposes the glossy finish did not lead to serious errors. The errors he had mentioned were calculated for a glossy lacquer.* As regards the Campbell-Freeth circuit, an important practical advantage was the use of an instrument (potentiometer) with a very long scale, enabling small readings as well as larger ones to be made with good precision. It might be that the short-circuit condition obtained with this circuit did not always result in a minimum departure from linearity over a limited

* See reference (29).

small range of photocurrents, but over a sufficiently extended range it would almost certainly do so.

He agreed with Mr. Mogford that a glass cover on a rectifier cell (and in some cases obstruction by the cell mounting) much increased the errors in illumination measurements. It was, however, important to avoid damp conditions when no cover was used, because damage due to moisture was irreparable.

The point of view of Dr. Walsh in emphasizing the difference between precision and accuracy was the one he himself had tried to stress. Photo-electric instruments were particularly useful for detecting small variations and differences in amounts of light and they could also, of course, be used for the measurement of stray light, which was a very useful practical application.

The use of a central or spiral contact on rectifier cells as an outlet for the current, in addition to the usual peripheral contact, would introduce difficulties. Perhaps one reason why the area of the contact was not increased might be that there would be additional internal leakage effects. The reduction in the effective area of the cell would not be very important because cells could be used in parallel. The use of several small cells in parallel was probably a better plan, and certainly more convenient to the manufacturer.

In reply to Mr. Maxted, he agreed that the paper described a good many disadvantages, but the extent to which photoelectric cells were used for photometry was good proof of their advantages, and one of the most important was repetition accuracy, or precision. The stability of the modern cell of either type was very good and the real problem was often to get stable and properly calibrated auxiliary instruments. Fortunately, at the National Physical Laboratory he did not have to face that difficulty. In the demonstration he had shown of linearity, he had used an illumination of the order of 10 ft.-c., which was reasonably low, but he would not be surprised to find with a 45 mm. cell and currents up to 100 milliamperes, departures from linearity of perhaps 4 or 5 per cent. That was his average experience.

The question of fatigue when testing gas lighting had been mentioned by Mr. Winstone, and it was quite possible there would be less fatigue than when testing certain other sources of light. The fatigue of the cell was very small in the green as compared with the red end of the spectrum. The use of a correction filter would in all cases reduce the radiation in the red end of the spectrum considerably, and so would reduce fatigue. That was a point in favour of the filter as against the use of correction-factors. The maximum safe working temperature for rectifier cells might be taken as 100 deg. F., but it did not follow that they would be unaffected if maintained at that temperature some considerable time.

As to the life testing of rectifier cells, referred to by Col. Edgcumbe, the figure of 1,000 hours at 200 ft.-c. was taken as an example of a test to which modern cells stood up very well. He had not carried such tests beyond 1,000 hours, but there might well be a limit to the life of the cells, which might be related to the total ampere hours of output drawn from them. It would be interesting to carry out tests over a longer time and at even higher illuminations, therefore. The maximum safe illumination for a rectifier cell depended largely on whether it was in circuit or not. If it were on short circuit a large current might flow through it, and probably 500 ft.-c. would be a safe working limit for 67 mm. cells. Smaller cells might be assigned rather higher limits.

The fatigue in rectifier cells was not, apparently, due to far infra-red or to radiant heat—that is to say, to radiation of wavelengths longer than those to which the cell responds photo-electrically.

The question of multi-range instruments mentioned by Professor MacGregor Morris was rather a long one to deal with in full. Systems which involved large changes in the resistance across the cell terminals on changing the ranges were to be deprecated. As an example of the reason for this one had only to consider the case of a cell in which the internal resistance was lowered considerably by some defect. The result would be a serious loss in output on a high resistance circuit, but very little on a low resistance circuit; so that calibration under the latter condition might be only slightly affected, though under the former it would no longer remain even approximately correct. In fact, the lower the resistance on any range, the better would be the stability of the calibration.

The use of a diaphragm with a fairly large number of holes, close to the surface of the cell, was permissible and would generally give consistent results. The surface of a cell might not be uniformly sensitive, however, and if the number of holes were limited to three or four, say, it would probably be

necessary always to use the diaphragm in the same orientation with regard to the cell.

When rectifier cells were used for sound-film purposes, as mentioned by Captain Murray, it was the alternating component of the output which was utilised. For a given amplitude of the light variations, this would fall seriously at the higher frequencies owing to the internal capacity of the cell itself (of the order 0.1 μfd. for a 45 mm. cell). Just what effect the frequency might have on the mean *direct* current from the cell was an interesting question, however, since cells used to measure fluorescent lamps operated on A.C. would generally be calibrated with a steady light source. No large errors would probably be involved, but he was unaware of any investigation of this point.

In reply to the chairman, he had at present no certain explanation to offer regarding the selective effect in the fatigue of rectifier cells. It seemed interesting to note, however, that the fatigue occurred for light of wavelengths in the region for which selenium had a high optical transmission. Possibly therefore penetration of the light below the surface of the selenium was in some way concerned in the effect. The recent improvement in rectifier cells had, he thought, resulted mainly from improvements in the technique of manufacture. That many different sputtered films, or surface treatments, had been tried, was evident from an inspection of cells on the market, and of the literature, but there was little doubt that the light sensitive element had, with few exceptions, always been pure selenium in the crystalline form.

Additions to List of Members.

The following applicants have been duly elected by the Council to membership in the Society, and their names have been added to the list of members:—

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